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Biological nitrogen removal in a modified anoxic/oxic process for piggery wastewater treatment

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ABSTRACT

Piggery wastewater is characterized by its high ammonium concentration and low COD/nitrogen ratio. The indiscriminate discharge of untreated piggery wastewater from scattered household pig farms has posed a potential risk of surface water pollution in rural areas of southern China. In this study, an anoxic/oxic (A/O) process with elastic fillers tightly packed in each tank was investigated for piggery wastewater treatment. Two anoxic tanks and two aerobic tanks were used in series and the hydraulic retention time of each was 24 h. Dissolved oxygen concentration in the aerobic tanks was intentionally controlled at below 2 mg L^{-1} for the implementation of nitritation. After sludge acclimation, three recycle ratios from 100 to 300% were tested. More than 90% of organic matter was removed from raw piggery wastewater despite recycle ratio values. However, the NH_4^+-N concentrations in the effluent slightly increased from 30 to 65 mg L^{-1} as the recycle ratio increased. Higher recycle ratio benefited the removal of total nitrogen (TN) and dramatically increased the nitrite accumulation rate in the aerobic tanks. The tightly packed elastic fillers successfully prevented the loss of sludge and increased the biomass in reactors. Moreover, the formation of biofilms on the surface of the elastic fillers developed simultaneous nitritation and denitrification in the aerobic tanks, which counted for approximately 30% of the total removed nitrogen in the proposed system. The employment of elastic fillers in A/O process effectively improved TN removal at a relatively smaller recycle ratio, and consequently reduced the running cost of recirculation for nitrogen removal.

Keywords: Anoxic/oxic process; Elastic filler; Nitritation; Simultaneous nitritation and denitrification; Piggery wastewater

1. Introduction

Piggery wastewater from pigsty cleaning contains high turbidity, high ammonium, and high organic matter. China is the biggest producer of pigs in the world with over 10 billion tons of piggery wastewater discharges annually [1]. Due to the poor management and insufficient sewage facilities, untreated piggery wastewater from scattered household pig farms is

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indiscriminately discharged into the water body nearby, which significantly increases the risk of surface water pollution, especially in rural areas of southern China. Nitrogenous compounds in piggery wastewater are important inducements for surface water eutrophication and threaten water ecosystem as well as drinking water safety for human beings [2]. Due to the low cost and high efficiency, biological nitrification and denitrification processes have been extensively used for nitrogen removal from piggery wastewater [3,4].

Conventional anoxic/oxic (A/O) process is well-known for its strong nitrogen removal. Compared with full nitrification and denitrification, nitritation and denitrification based on the pathway of NO_2^- theoretically requires less oxygen for ammonium oxidation and less carbon source for nitrite reduction [5]. Since the concept was first put forward in 1975, nitritation and denitrification has been well investigated [6]. How to practically enrich ammonia-oxidizing bacteria (AOB) and inhibit nitrite-oxidizing bacteria (NOB) is the key point for its application [7]. Several factors, e.g. dissolved oxygen concentration (DO) [8], temperature [9], pH [10], and sludge retention time (SRT) [11], can be intentionally controlled for the successful implementation of high ammonium removal via nitrite. Therein, low DO concentration generally benefits the accumulation of nitrite in the aerobic tank. When DO is between 0.7 and 1.4 mg L^{-1}, the nitrite accumulation is significant [7]. Higher DO improves the NOB activity and consequently decreases the nitrite accumulation ratio (NAR) in the nitrifying solution. However, extremely low DO concentration decreases the AOB activity and deteriorates the whole performance of the aerobic tank in terms of both ammonium and organic matter removals. Moreover, NOB are more sensitive to free ammonia (FA) than AOB [12]. The tolerance concentration of FA is around 0.1–1.0 mg L^{-1} for NOB while 10–150 mg L^{-1} for AOB [13]. FA concentration increases as the solution pH increases. Therefore, nitritation usually takes place in a weakly alkaline solution. The optimum pH was reported to be between 8.0 and 8.4 [14]. Since DO, pH, and ORP are easily online monitored, real-time control is often used to implement nitritation and denitrification [7,15,16].

Because nitritation and denitrification is energy-effective and less restricted to the assimilable organic matter in the influent, it is very attractive for nitrogen removal from high-strength ammonium wastewater, such as municipal landfill leachate [17], septic tank wastewater [18], slaughterhouse wastewater [19], digested food wastewater [20], etc. Piggery wastewater contains high concentrations of chemical oxygen demand (COD) and NH_4^+-N. Since the organic matter is highly assimilable, COD removal efficiency is generally high. However, total nitrogen (TN) removal from piggery wastewater is limited to the low COD/nitrogen ratio (COD/N). External carbon source is requisite to achieve a high TN removal in conventional full nitrification and denitrification. Therefore, the running cost is high.

In this study, an A/O system modified with elastic fillers in the anoxic and aerobic tanks was used for piggery wastewater treatment. In order to overcome the restriction of low COD/N on TN removal, nitritation was implemented by decreasing DO in the aerobic tanks. The system was conducted without additional carbon source. The introduction of the tightly packed elastic fillers was to retain the biomass in each reactor and create conditions for simultaneous nitritation and denitrification (SND) in the aerobic tanks. The effects of recycle ratio on both organic carbon and nitrogen removals were investigated, and the conversion of NH_4^+-N to NO_x^--N was discussed.

2. Materials and methods

2.1. Raw water

Piggery wastewater used in this study was collected from a household pig farm in Hebei Province, China. It was generated from pigsty cleaning. The pig excrement was first removed out of pigsty and collected as agricultural fertilizer. The residuals as well as urine were then flushed with tap water. The raw wastewater ran into a pond by gravity, where the suspended solids were fully settled. The supernatant was pumped into water drums by a pump equipped with a 4 mm-diameter mesh at the inlet. The loaded water drums were transported to the laboratory, and kept in the refrigerator before use. The main characteristics of the filtrated wastewater are listed in Table 1. The average NH_4^+-N concentration was around 900 mg L^{-1}, and constituted the majority of TN in raw wastewater. Since NO_2^- and NO_3^- were not detected, differences in concentrations between NH_4^+-N and TN were presumably due to the presence of organic nitrogen. The COD/N was 2.2–3.6, indicating that external carbon source was required in order to guarantee satisfying denitrification via NO_3^- [21].

2.2. Experimental system

The piggery wastewater treatment system employed in this study consisted of two anoxic tanks and two aerobic tanks in series (Fig. 1). The effective volume of each tank was 12 L. Elastic fillers purchased

Table 1
Characteristics of the piggery wastewater used in this study

COD (mg L^{-1})	BOD_5 (mg L^{-1})	NH_4^+-N (mg L^{-1})	TN (mg L^{-1})	Alkalinity (mg L^{-1}, as $CaCO_3$)	pH
3,141 ± 703	1,732 ± 489	894 ± 136	1,029 ± 85	2,096 ± 269	8.28 ± 0.26

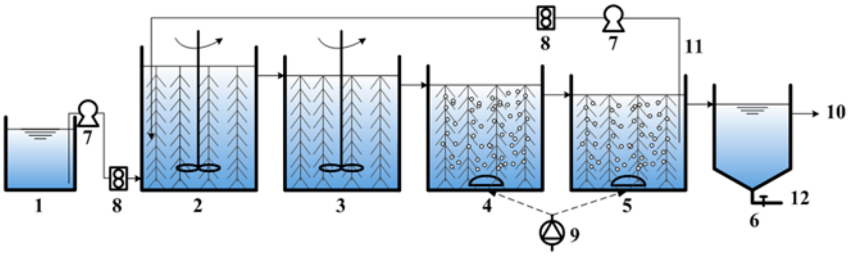

Fig. 1. Schematic diagram of the modified A/O process for piggery wastewater treatment. (1) raw wastewater tank; (2) anoxic tank 1#; (3) anoxic tank 2#; (4) aerobic tank 1#; (5) aerobic tank 2#; (6) settling tank; (7) pump; (8) liquid flow meter; (9) blower; (10) effluent; (11) recirculation; and (12) excess sludge.

from Tehuan Water Treatment Equipment Co., Ltd, China, were tightly packed in each tank (1 piece per 50 cm^2). Surplus sludge from Jizhuangzi Sewage Treatment Plant in China was collected to inoculate anoxic and aerobic tanks. The initial biomass in each tank was around 8,400 mg MLSS L^{-1}. The anoxic tanks were equipped with mechanical stirrers to gently mix the solution and sludge. DO in aerobic tanks was regulated by aeration intensity and intentionally kept below 2 mg L^{-1} for implementation of nitritation. The temperature of anoxic and aerobic tanks was kept at 32 ± 1˚C by a hot water jacket. A submersible pump in the final aerobic tank was employed to intermittently recycle the nitrifying solution to the first anoxic tank for denitrification. The pump was turned on hourly. Its running duration was used to regulate the recycle ratio (R), which was calculated by dividing the amount of recycled solution by that of influent in an hour. The effluent of the final aerobic tank entered a settling tank before discharge. The tightly packed fillers successfully retained the sludge in each tank. Therefore, the sludge amount in the settling tank was quite small (less than 0.2 g MLSS L^{-1}) and treated as surplus sludge without recycle.

2.3. Experimental procedure

The whole experiment was divided into two phases. Specific conditions of different experimental runs in either phase are listed in Table 2. Phase I was conducted to acclimate the bacteria to high NH_4^+-N concentration in the influent. Piggery wastewater was diluted by tap water to reduce ammonia inhibition on bacterial growth and activity. Dilution ratio (n) was initially 300% (Run 1) and then decreased to 200% (Run 2). After nitritation was established in aerobic tanks, dilution ratio decreased to 100% and the nitrifying effluent was recycled to the first anoxic tank with a recycle ratio (R) of 100% (Run 3). Phase II was conducted to investigate the effect of recycle ratio on organic matter and TN removal (Runs 4–6). Piggery wastewater without dilution was fed into the system. Continuous operation was carried out throughout the entire experiment. The hydraulic retention time (HRT) of each anoxic and aerobic tank was 24 h, and the total HRT of the entire process was 96 h.

Table 2
Operating conditions for different experimental runs

		Date	Dilution ratio	Recycle ratio
Phase I	Run 1	1–17	300%	0
	Run 2	17–33	200%	0
	Run 3	33–51	100%	100%
Phase II	Run 4	51–66	0	100%
	Run 5	66–81	0	200%
	Run 6	81–93	0	300%

2.4. Analytical methods

COD was measured using the potassium dichromate oxidation method (DR2800, HACH). TN, NH_4^+-N, NO_2^--N, and NO_3^--N were analyzed by a spectrophotometer (UV-2550, Shimadzu) according to Standard Methods [22]. Both DO and solution pH were determined using a portable multi-parameter analyzer (sensION 156, HACH). The biofilm morphology on the elastic filler surface was analyzed by a scanning electron microscope (SEM) (S-4800, Hitachi). The filler samples were pretreated before analysis according to reference [23].

3. Results and discussion

3.1. COD removal

The organic matter in raw piggery wastewater was highly biodegradable ($BOD_5/COD = 0.58$); therefore, COD removal was not supposed to pose a problem in the present system. Fig. 2 shows the COD removal in different runs. Under low organic loading rates (OLR) without recirculation (0.10 kg COD m^{-3} d^{-1} for Run 1 and 0.13 kg COD m^{-3} d^{-1} for Run 2), the overall COD removal was less than 50%. This was probably because the inoculated sludge had not yet been adapted to the influent. After dilution ratio decreased to 100% and recirculation started (Run 3), the COD removal gradually increased to more than 75% and the anoxic tanks removed much more COD than the aerobic tanks did. Besides the successful acclimation of micro-organisms in the anoxic tanks, the occurrence of denitrification as a result of the recirculation of nitrifying effluent also contributed to the COD removal. Undiluted piggery wastewater was not fed into the system until nitritation in the aerobic tanks and denitrification in the anoxic tanks were both stable (Phase II). The OLR was around 0.67 kg COD m^{-3} d^{-1}. The increase in recycle ratio from 100 to 300% slightly affected the overall COD removal. More than 90% of COD was finally removed. This result was comparable with the treatment of pig manure digester liquor by intermittently aerated sequencing batch reactors [24].

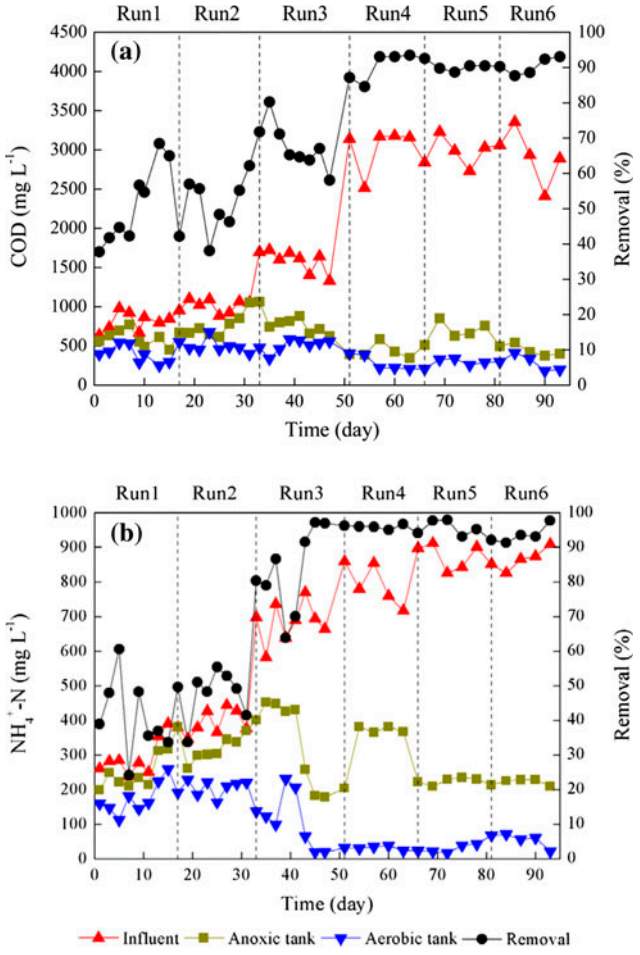

Fig. 2. COD (a) and NH_4^+-N (b) removals in the modified A/O process.

3.2. NH_4^+-N removal

Successful ammonium removal was crucial in the effective treatment of piggery wastewater. In order to avoid the strong inhibition on sludge acclimation, the ammonium concentration fed into the modified A/O system was seriously controlled in Phase I based on the nitritation performance in the aerobic tanks. Even though ammonium loading rates (ALR) were only 0.073 and 0.098 kg N m^{-3} d^{-1} in Run 1 and 2, the overall NH_4^+-N removal was less than 50% (Fig. 3). This was probably due to the slow growth of autotrophic nitrifiers. The anoxic tanks also contributed to the

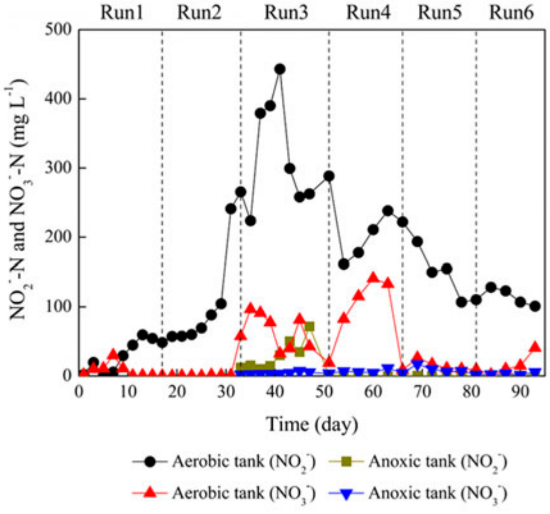

Fig. 3. NO_2^--N and NO_3^--N concentrations in the modified A/O process.

NH_4^+-N removal in Run 2 as a result of the microbial assimilation. After dilution ratio decreased to 100% and recycle ratio of 100% was used to start the denitrification in the anoxic tanks (Run 3), the overall NH_4^+-N removal dramatically increased to more than 80% on Day 33. However, it decreased to 65–70% during Day 35–Day 40. This was probably because bacteria needed time to acclimate to the increase in OLR and ALR in Run 3. The NH_4^+-N removal efficiency gradually increased to more than 90% thereafter. On Day 45, the NH_4^+-N concentration in the effluent of aerobic tanks was only 19 mg L^{-1}, indicating the successful cultivation and enrichment of nitrifiers. In Phase II, the ALR value was maintained at 0.197 kg N m^{-3} d^{-1}. The increase in recycle ratios from 100 to 300% slightly decreased the NH_4^+-N removal from 96 to 93%. Since nitrification bacteria grow slowly, it is usually difficult to enrich them in conventional active sludge reactor in a short period [25]. The employment of tightly packed fillers in the proposed system effectively retained the suspended sludge and formed biofilms on their surface. As a result, SRT was extended and nitritation bacteria were better enriched. The NH_4^+-N concentration in the effluent was less than 60 mg/L from Day 51, which was in compliance with the maximum contaminant level for NH_4^+-N in Chinese national discharge standards for livestock and poultry breeding.

3.3. NO_2^--N and NO_3^--N

The molar ratio between NO_2^- and NO_x^-, namely NAR, is usually used to investigate the implementation of nitritation. The generation and transformation of NO_2^- and NO_3^- are closely related to the metabolic processes of nitrifier and denitrifier, and affected by pH, carbon source, DO, etc. [26,27]. The NO_2^- and NO_3^- concentrations in the effluents of anoxic and aerobic tanks in different runs are shown in Fig. 3. Since DO was intentionally kept below 2 mg/L, nitritation was designed to be the dominant nitrification process. However, NO_3^- (10–30 mg N L^{-1}) was detected in the effluent of the aerobic tanks at the very beginning (Day 3−Day10). After 10 days of operation, NO_3^- disappeared and NO_2^- appeared instead. As dilution ratio decreased from 300 to 200% (Run 2), the NO_2^--N concentration in the aerobic effluent markedly increased from 55 to 241 mg L^{-1}, indicating the effective enrichment of AOB in the aerobic tanks. Nitritation was successfully started up under the condition of low DO by the end of Run 2. Nitrifying solution in the aerobic tank was recycled to the anoxic tanks for the acclimation of denitrification bacteria in Run 3. The NO_2^--N concentration decreased from 300 to 400 mg L^{-1} in the recycled nitrifying solution to 30 mg L^{-1} in the anoxic effluent, indicating the presence of denitrification bacteria in the anoxic tanks. In Phase II, with the increase in recycle ratio from 100 to 300%, the NH_4^+-N concentration entering the aerobic tanks decreased due to the strong denitrification in the anoxic tanks. As a result, the NO_x^--N concentration in the aerobic effluent decreased. A significant amount of NO_3^-–N (around 130 mg L^{-1}) was detected in the aerobic effluent in Run 4; however, it dramatically decreased to 13 mg L^{-1} in the subsequent Run 5. The NAR value was more than 90% in Runs 5 and 6; therefore, nitritation was recovered as the recycle ratio increased from 100 to 300%. The reason for the low NAR value in Run 4 will be discussed later. With the increase in recycle ratio, more NO_x^- was recycled to the anoxic tanks. As a result, more carbon source was required for denitrification. However, the remaining NO_2^--N and NO_3^--N were merely 3 and 1 mg L^{-1} in the anoxic effluent, respectively, which indicated that denitrification in the anoxic tank was effective and no restriction on carbon source was observed.

The processes of nitritation and denitrification were accompanied by the consumption and production of alkalinity in wastewater. As a result, the solution pH varied in different runs. When the recycle ratio was 100% in Run 4, the generated alkalinity in denitrification was not enough for the compensation of that consumed in nitritation. As a result, the solution pH in the aerobic tanks decreased to 7.1–7.6. The increase in recycle ratio to 200 and 300% (Runs 5 and 6) provided more NO_x^- for denitrification in the anoxic tanks. More alkalinity was therefore generated. The balance of alkalinity consumption and production was achieved. The solution pH of the aerobic effluent maintained at 8.2–8.7.

FA concentration is important for the implementation of nitritation as well. Its concentration was calculated based on the solution pH, total ammonium concentration, and temperature (t, ℃) [13]:

$$\text{FA as NH}_3\ (\text{mg L}^{-1}) = \frac{17}{14} \times \frac{\text{total ammonium as N}\ (\text{mg L}^{-1}) \times 10^{\text{pH}}}{\exp\left[6344/\ (273 + t\ (^\circ\text{C}))\right] + 10^{\text{pH}}} \quad (1)$$

The FA profile of different runs is shown in Fig. 4. FA with concentration higher than 10 mg L^{-1} strongly inhibits the activity of both AOB and NOB, and deteriorates the overall nitrification [13]. On the other hand, compared with AOB, NOB is more sensitive to the toxicity of FA [28]. The oxidation of NO_2^- to NO_3^- is inhibited when the FA concentration is more than 1 mg L^{-1}. Therefore, nitritation can be achieved by

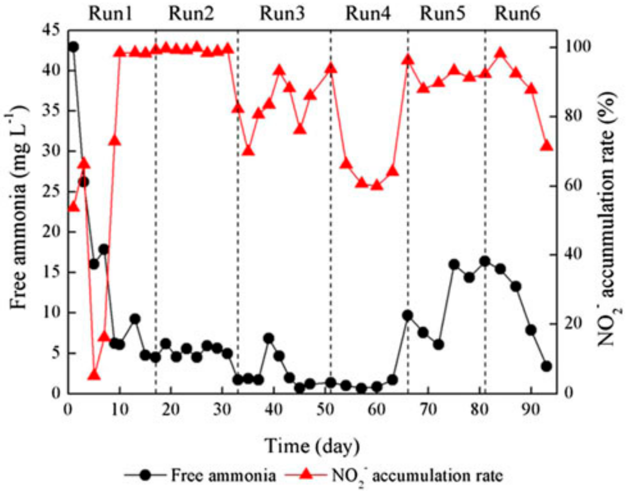

Fig. 4. FA and NAR in the modified A/O process.

proper control of the aqueous FA concentration. In Run 2, when the FA concentration was around 5 mg L^{-1}, the NAR value was higher than 98%. However, once the FA concentration decreased to less than 2 mg L^{-1} (Run 3), the activity of NOB recovered quickly and NO_3^- began to accumulate. This was also found in Run 4. When the FA concentration in the aerobic tanks decreased to 0.7–1.4 mg L^{-1}, the NAR value decreased to approximately 60%. In Runs 5 and 6, with the increase in pH in the aerobic tanks, the FA concentration increased to 6.1–16.4 mg L^{-1}. As a result, the activity of NOB was inhibited by FA again and the NAR value increased to higher than 90%. However, by the end of Run 6, with the decrease in FA concentration in the aerobic tanks, the NAR value gradually decreased. Based on the above results, it can be concluded that in the proposed system, FA in the aerobic tanks also helped to implement and stabilize nitritation besides the intentionally low DO concentration. Nitritation using the FA inhibition was proved to be an effective technique for the treatment of swine wastewater digester liquor containing high concentrations of ammonium [29]. The maintenance of FA concentration at approximately 0.5 mg L^{-1} benefited nitritation for a 120 d running in a nitrifying reactor with acryl-fiber biomass carrier. However, the FA concentration for stable nitritation was much higher in this study. This was attributed to the protection of NOB by the elastic fillers tightly packed in the aerobic tanks. Same protective effect was also reported in a nitritation reactor using immobilized polyethylene glycol gel carriers [30]. The carries provided a preventive cover to the inside AOB; therefore, the inhibition of FA on AOB activity decreased. Successful nitritation was achieved at an average FA concentration of approximately 50 mg L^{-1}. An even higher FA concentration of 60 mg L^{-1} was also reported in a membrane bioreactor (MBR) system for nitritation implementation [3].

3.4. TN removal

TN concentration profile and its removal in Phase II are shown in Fig. 5(a). With the recycle ratio increasing from 100 (Run 4) to 200% (Run 5), the average TN removal efficiency increased from 60 to 80%, and the TN concentration in the aerobic effluent decreased from 385 to 212 mg L^{-1}. When the recycle ratio further increased to 300% in Run 6, the TN removal was not improved significantly. Nitrogen removal from synthetic wastewater (similar to anaerobically pretreated piggery wastewater) was investigated in an A^2O process by Jih et al. [31]. In their study, due to the deficiency in organic carbon

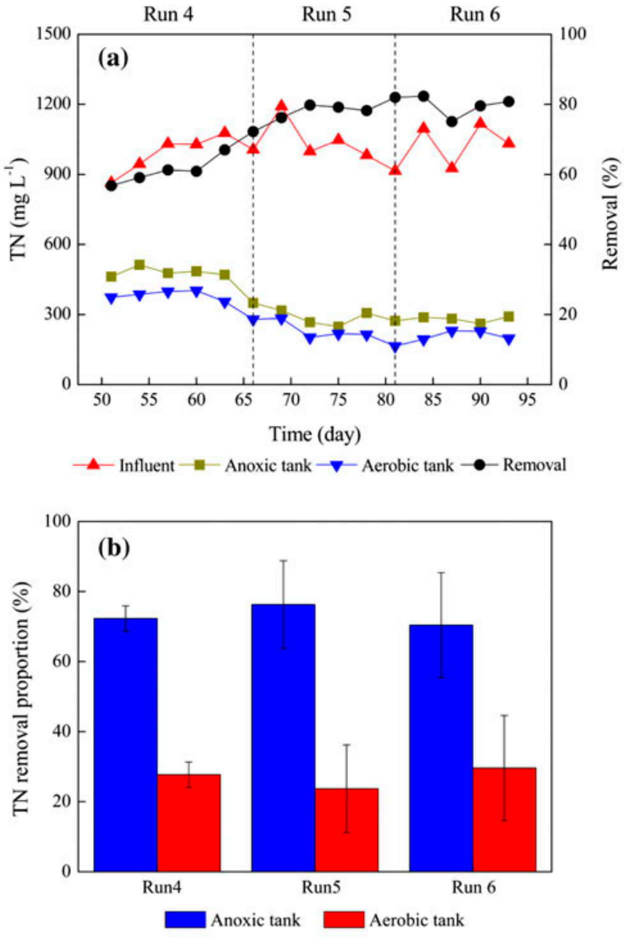

Fig. 5. TN removal (a) in the modified A/O process and its removal proportion (b) in the anoxic and aerobic tanks.

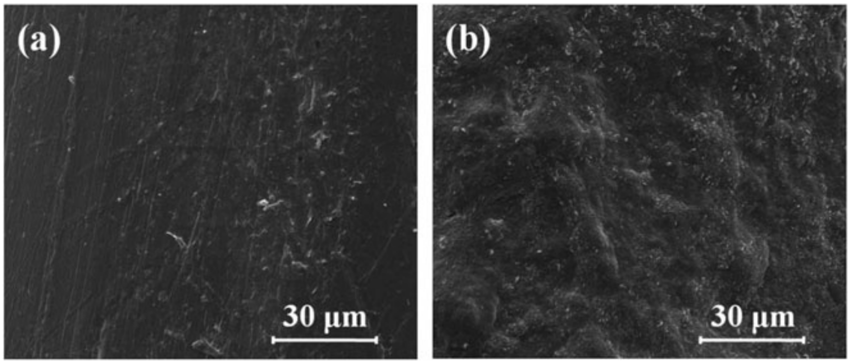

Fig. 6. SEM images (×2,000) for pristine elastic fillers (a) and fillers installed in the aerobic tank for four months (b).

(COD/N was around 3.1), TN removal efficiency through full nitrification and denitrification was around 50% and the recycle ratio only imposed a slight effect on TN removal. Serious restriction of organic carbon on TN removal was also observed in the treatment of swine wastewater by combining submerged MBR and anaerobic upflow bed filter reactor by Shin et al. [32]. Even though the influent COD/N ratio of the present study was equivalent to these two previous studies, the implementation of nitritation in the aerobic tanks successfully decreased the need of organic carbon for denitrification. Therefore, the TN removal efficiency was much higher (around 80% at recycle ratio of 2) and increased with the recycle ratio. Similar TN removal efficiency was also reported by Rajagopal et al. who obtained an TN elimination of 72–74% by nitritation and denitrification in an A/O continuous stirred tank reactor for digested piggery wastewater treatment [33].

It should also be noted that the TN concentration in the aerobic effluent was always smaller than that in the anoxic effluent despite recycle ratio values. Therefore, SND in the aerobic tanks also contributed to the TN removal in the modified A/O system. The respective contributions of anoxic and aerobic tanks to TN removal were quantitatively analyzed based on the TN mass balance. The equations were as follows:

$$P_{\mathrm{An}} = \frac{[\mathrm{TN}]_{\mathrm{in}} + R[\mathrm{TN}]_{\mathrm{eff}} - (1+R)[\mathrm{TN}]_{\mathrm{An-2}}}{[\mathrm{TN}]_{\mathrm{in}} - [\mathrm{TN}]_{\mathrm{eff}}} \times 100\% \tag{2}$$

$$P_{\mathrm{Ox}} = \frac{(1+R)\left([\mathrm{TN}]_{\mathrm{An-2}} - [\mathrm{TN}]_{\mathrm{eff}}\right)}{[\mathrm{TN}]_{\mathrm{in}} - [\mathrm{TN}]_{\mathrm{eff}}} \times 100\% \tag{3}$$

where P_{An} and P_{Ox} represented the TN removal proportions in aerobic and anoxic tanks, respectively; [TN] represented the TN concentration, mg L^{-1}; R represented the recycle ratio; the subscripts of in, eff, and An-2 represented the influent, effluent, and anoxic tank 2#, respectively. It can be seen clearly in Fig. 5(b) that the anoxic tanks removed more nitrogen than the aerobic tanks did despite recycle ratio values. More than 70% of the removed TN in the proposed system was attributed to denitrification via $\mathrm{NO_2}^-$ in the anoxic tanks, while approximate 30% was attributed to SND in the aerobic tanks. The contribution proportion of TN removal between anoxic and aerobic tanks did not change significantly with recycle ratio. SND and denitrification was also observed in nitritation treatment for anaerobic digestion liquor of swine wastewater using swim-bed technology [34]; however, the overall TN removal efficiency was only 10%. In the present study, the TN removal in the aerobic tanks was much stronger, counting for around 25% of the total TN removal. This was mainly attributed to the use of tightly packed fillers. These fillers retained a large quantity of biomass on the surface and created better microenvironment for the survival and growth of denitrification bacteria in the aerobic tanks. Fig. 6 shows the SEM images of pristine elastic fillers and those used in the aerobic tanks for four months. The elastic fillers were made of polyolefin and the pristine surface was clean and smooth (Fig. 6(a)). After four month running, stable biofilms were clearly seen on the filler surface (Fig. 6(b)). The development of SND in the aerobic tanks markedly improved the TN removal under relatively low recycle ratio. The cost of recirculation was therefore reduced. Moreover, the cooperation of denitrification in the anoxic and aerobic tanks guaranteed a highly efficient and stable TN removal in the proposed system.

The tightly packed fillers also increased SRT and benefited the growth of autotrophic nitritation bacteria in the aerobic tanks. It cost only one month for the proposed system to establish reliable nitritation. Previous study indicated that the ratio of ammonium concentration to AOB was a key factor for complete biological removal of ammonium [35]. Large AOB populations were preferred for the treatment of high-strength nitrogen wastewater as long as the inhibition of ammonia was not significant. Thanks to the effective accumulation of AOB in the biofilms on the surface of the fillers, satisfying nitritation was obtained in the present study even when the ALR was as high as 0.2 kg N m^{-3} d^{-1}. This was another advantage of the introduction of tightly packed elastic fillers in the A/O system for the treatment of piggery wastewater containing high ammonium.

4. Conclusion

A modified A/O process with elastic fillers tightly packed in each tank was developed for the treatment of piggery wastewater containing high ammonium. In order to overcome the restriction of low COD/N ratio on denitrification, nitritation was conducted by the low DO concentration in the aerobic tanks. FA remaining in the aerobic tanks also benefited the implementation of nitritation in the proposed system as it inhibited the NOB activity. The NAR value was higher than 90% when the recycle ratios were 200 and 300%. The employment of tightly packed elastic fillers effectively accumulated AOB in the biofilms on their surface. Therefore, the removal of NH_4^+-N was higher than 90% even when its concentration in the influent was more than 900 mg L^{-1}. The biofilms also introduced SND in the aerobic tanks, which contributed approximately 30% to the overall nitrogen removal. The cooperation of denitrification in the anoxic and aerobic tanks guaranteed the highly efficient and stable TN removal. Around 80% of TN was removed at recycle ratio of 200%. The effluent quality of the treated piggery wastewater was in compliance with the national discharge standard of pollutants for livestock and poultry breeding.

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